Iranian Journal of Engineering Geology
Spring 2020, Vol.13, No.1

Failure Modes Analysis of Sandstones (Case Study: Markazi Province Sandstones)

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Abstract

The aim of this study is analyzing the failure modes of sandstones related to Markazi Province using compressive strength changes. For this purpose, the fracture modes of five different types of sandstones with different compressive strength values have been studied experimentally and numerically. Also, The effect of failure modes on uniaxial compressive strength was quantified. block samples were collected from different sandstone formations located in northern part of Markazi province. These sandstones were divided into five types based on the textural and mineralogical characteristics. These samples were subjected to uniaxial compressive strength testing. Examination of the fracture modes showed that simple shear mode occurred at low values of strength and it changes to multiple extension mode with increasing the compressive strength. The dominant failure mode for types 1, 2 and 4 is simple shear and for types 3 and 5 is multiple extension. Investigation of failure modes in different strength ranges showed that the dominant failure modes up to 140 and over 140 MPa are simple shear and multiple extension, respectively. Therefore, strength of 140 MPa was considered as the transisson point. Also, in this study, the failure modes of the experimental samples were numerically simulated using PFC^{2D} software. The results of numerical modeling showed a good agreement with the experimental results.

Keywords: *sandstones, failure mode, UCS,* PFC^{2D}

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Extended Abstract:

1. Introduction

Microscopic discontinuities vary the values of mechanical properties of rocks such as uniaxial compressive strength, even when the tested samples have the same mineralogical composition. Some parameters such as location, orientation, size, density, and extent of microscopic discontinuities control different failure modes. When, examining the rock strength, the failure modes of the sample and rock mass is not sufficiently considered. However, this parameter can explain the reason for a large range of strength values obtained from experimental tests of rock samples. Basu (2013) and Szwedzicki (2007) showed that with the same mineralogical composition, the range of uniaxial compressive strength may be high and different failure modes can be seen. This is due to the differences in microscopic discontinuities, especially micro cracks. The application of numerical studies for modeling the fracture process has made to considerable progress in understanding of the fracture process in brittle rocks (Taoying, 1989). Due to the time consuming and costly in the experimental and in situ tests, numerical modeling is a good approach to better understand experimental tests. The purpose of this study was to determine failure modes in different types of sandstones under uniaxial compressive strength test (UCS) and also to investigate the relationship between failure modes and UCS values. In this study, also the failure modes and the relationship between them and rock strength were investigated using numerical fracture simulation.

2. Materials and methods

Block samples with approximate dimensions of 30×50×50 cm were collected from different types of sandstones. For petrographic studies, thin sections of collected samples were prepared. Petrographic studies includes mineralogical study of grains, cement and also modal analysis to determine the volumetric percentages of each type of sandstone. The Point counting technique proposed by Gezi-Dickinson (Ingersoll et al 1984) has been used in order to perform the modal analysis. The physical properties of the studied sandstones includes specific gravity (Gs), dry and saturation density (γ_d, γ_{sat}), porosity (n) and wave velocity (Vp). The porosity and density of the solid particles were measured using saturation method. All specimens were tested according to the standard method proposed by (ISRM 1981). In order to determine the mechanical properties of the studied sandstones, the UCS test was performed in accordance with ISRM (1981). Software Particle Flow Code 2D (PFC^{2D}) developed by Itasca (Itasca Consulting Group Inc. 2008) was also used to simulate the failure process and also the failure modes.

3. Analysis of failure modes

In order to investigate the failure modes in this study, sandstone samples were subjected to uniaxial compressive tests. Shamu and Szwedzicki (1999) introduced five failure modes for cylindrical specimens of hard and brittle rocks including simple extension, multiple extension, multiple fracturing, simple shear and multiple shear. In type 1, simple shear failure with 12 samples is the most frequent failure mode observed. The dominant fracture mode in type 2 specimens is simple shear (13 specimens). The most failure mode observed in types 3, 4 and 5 were multiple extension, simple shear and multiple extension, respectively. Multiple shear failure mode were not observed in of the 3, 4 and 5 types. Examination of the variations trend of failure modes with respect to compressive strength values of all sandstone samples showed that as the strength increases, the

number of shear failure modes decreases. As this failure mode up to 140 MPa strength is the dominant failure mode and then it decreases. However, as the strength increases, the multiple extension failure increases and for values exceeding 140 MPa, it's dominant. The failure modes obtained from numerical simulations showed a good agreement with the experimental failure modes. In the numerical model of type 2 sandstone, the frequency of shear cracks is much higher than that of tensile cracks. The numerical model of this type showed the lowest average value of strength due to the high number of shear cracks in the model, which with their integration a simple shear failure mode was resulted. For type 5, which has the highest average UCS, the frequency of tensile cracks is much higher than shear cracks. In this type, a simple extension failure mode has occurred.

4. Conclusion

Despite of same mineralogy, variations in uniaxial compressive strength (UCS) values of the samples in each type are due to the failure modes that are indicative of microscopic discontinuities conditions. Based on the results, UCS variations in type 2 samples, they had the same failure mode (62% of the specimens), less than those types. Therefore, it was found that when most failure modes were the same, the range of uniaxial compressive strength was low.

The use of numerical simulation made it possible to investigate the experimental failure modes. It was also found that the frequency of tensile and shear cracks is the basis of the formation of different failure modes is a function of the strength values of the rock.

References:

Akesson, U., Hansson, J., Stigh, J., 2004. Characterization of microcracks in the Bohus granite, western Sweden, caused by uniaxial cyclic loading. Eng Geol, 72:131–142.

Anon., 1979. Classification of rocks and soils for engineering geo logical mapping. Part 1—Rock and soil materials. Bulletin of the International Association of Engineering Geology, 19, 364–371.

Bahaaddini, M., Sharrock, G., Hebblewhite, B.K., 2013. Numerical investigation of the effect of joint geometrical parameters on the mechanical properties of a non-persistent jointed rock mass under uniaxial compression. Computers and Geotechnics, 49: 206-25.

Basu., A. 2006. Mechanical characterization of granitic rocks of Hong Kong by improved index testing procedures with reference to weathering induced microstructural changes. PhD thesis, The University of Hong Kong.

Basu, A., Celestino, T.B., Bortolucci, A.A., 2009. Evaluation of rock mechanical behaviours under uniaxial compression for different weathering grades. Rock Mech Rock Eng, 42:73–93.

Basu, A., Mishra, D.A., Roychowdhury, K., 2013. Rock failure modes under uniaxial compression, Brazilian, and point load tests. Bull Eng Geol Environ, 72:457–475.

Bobet, A., 1997. Fracture Coalescence in Rock Materials: Experimental Observations and Numerical Predictions, MIT, Massachusetts, Cambridge, 1997.

Deere, D.U., Miller, R.P., 1966. Engineering classification and index properties for intact rock. Tech. Rep. AFWL-TR- 65-116, Air Force Weapons Lab., Kirtland Air Force Base, 308 pp.

Diederichs, M., 2003. Manuel rocha medal recipient rock fracture and collapse under low confinement conditions. Rock Mech Rock Eng, 36(5):339–381.

Diederichs, M.S., 1999. Instability of hard rockmasses: the role of tensile damage and relaxation. Ph.D Thesis, University of Waterloo, Canada.

Dyskin, A.V., Sahouryeh, R.J.Jewell. 2003. Influence of Shape and Locations of Initial 3-D Cracks on Their Growth in Uniaxial Compression. Engineering Fracture Mechanics, 70:2115-2136.

Folk, E., 1980. Petrography of Sedimentary Rocks, Hemphill Publishing Company, 182p.

Hudyma, N., Avar, B.B., Karakouzian, M., 2004. Compressive strength and failure modes of lithophysae-rich Topopah Spring Tuff specimens and analog models containing cavities. Eng Geol, 73:179–190.

Ingersoll, R.V., Bullard, T.F., Ford, R.L., Grimm, J.P., Pickle, J.D., Sars, S.W., 1984. The effect of grain size on detrital modes: a test of the Gazzi–Dickinson point-counting method. Journal of Sedimentary Petrology 54 (1), 103–116.

ISRM., 1981. The complete ISRM Suggested methods for rock characterization, testing and monitoring, edited by Brown. Pergamon Press, Oxford, UK.

Itasca Consulting Group Inc., 2004/2005. PFC2D/3D (Particle Flow Code in 2/3 Dimensions) User's Guides, Minneapolis, MN, USA.

Jaeger, J.C., Cook, N.G.W., 1979. Fundamentals of rock mechanics, 3rd edn. Chapman & Hall, London.

Klein, E., Baud, P., Reuschle, T., Wong, T.F., 2001. Mechanical behavior and failure mode of Bensteim sandstone under triaxial compression. Phys Chem Earth (A) 26:21–25.

Maji, V.B., 2011. Understanding failure mode in uniaxial and triaxial compression for a hard brittle rock. In: Proceedings of the 12th ISRM international congress on rock mechanics. CRC Press/ Balkema, Leiden, pp 723–726.

Martin, C., Chandler, N., 1994. The progressive fracture of Lac du Bonnet granite. Int J Rock Mech Min Sci Geomech Abstr Pergamon, 31(6):643–659.

Imani, M., Nejati, H.M., Goshtasbi, K., 2017. Dynamic response and failure mechanism of Brazilian disk specimens at high strain rate. Soil Dynamics and Earthquake Engineering. 100: 261–269.

Mogi, K., 2007. Experimental rock mechanics. Taylor & Francis Group, London.

Park, C.H., Bobet, A., 2010. Crack Initiation, Propagation and Coalescence from Frictional Flaws in Uniaxial Compression. Engineering Fracture Mechanics, 77: 2727-2748.

Potyondy, D.O., 2012. A flat-jointed bonded-particle material for hard rock. In: Proceedings of the 46th US Rock mechanics/geomechanics symposium. American Rock Mechanics Association.

Potyondy, D.O., Cundall, P.A., 2004. A bonded-particle model for rock. Int. J. Rock Mech. Min. Sci, 41(8):1329-64.

Sammis, C.G., Ashby, M.F., 1986. The failure of brittle porous solids under compressive stress state. Acta Metall, 30:511–526.

Santarelli, F.J., Brown, E.T., 1989. Failure of three sedimentary rocks in triaxial and hollow cylinder compression tests. Int J Rock Mech Min Sci Geomech Abstr, 26:401–413.

Schopfer, M.P., Abe, S., Childs, C., Walsh, J.J., 2009. The impact of porosity and crack density on the elasticity, strength and friction of cohesive granular materials: insights from DEM modelling. Int J Rock Mech Min Sci, 46(2):250–261.

Shunchuan, W.u., Xueliang, X.u., 2016. A Study of Three Intrinsic Problems of the Classic Discrete Element Method Using Flat-Joint Model. Rock Mech Rock Eng, 49(5): 1813–1830.

Szwedzicki, T., 2007. A Hypothesis on Modes of Failure of Rock Samples Tested in Uniaxial Compression Rock Mech. Rock Engng, 40(1): 97–104.

Szwedzicki, T., Shamu, W., 1996. Detection of planes of weakness in rock samples using nondestructive testing method. In: Proc., '96 International Symposium on Mining Science and Technology, China. AA Balkema, Rotterdam, pp 759–763.

Szwedzicki, T., Shamu, W., 1999. The effect of material discontinuities on strength of rock samples. In: Proc., Australasian Institute of Mining and Metallurgy, 304(1): 23–28.

Taoying, l., Ping, C., 1989. Failure Mechanisms Of Brittle Rocks under Uniaxial Compression. Journal of Theoretical and Applied Mechanics, Sofia, 47(3): 59-80.

Xueliang, X., Shunchuan, W., Yongtao, G., Miaofei, X., 2016. Effects of Micro-structure and Micro-parameters on Brazilian Tensile Strength Using Flat-Joint Model Rock Mech Rock Eng, 49:3575–3595.

Zhang, Q., Zhu, H., Zhang, L., Ding, X., 2012. Effect of micro-parameters on the Hoek–Brown strength parameter mi for intact rock using particle flow modeling. In: The 46th US rock mechanics geomechanics symposium, ARMA-12-672.